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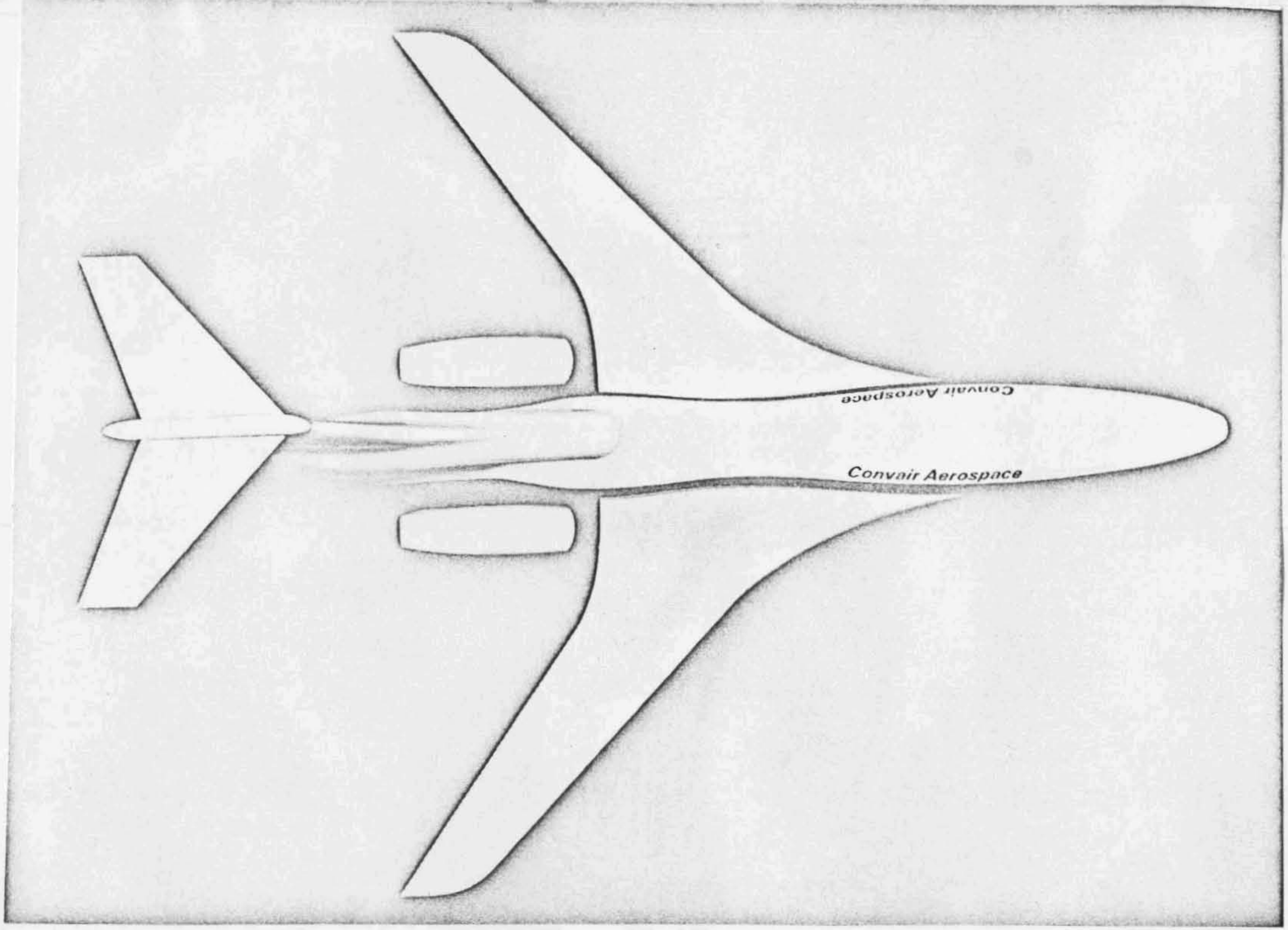
ABSTRACT. Flow phenomena encountered in the vicinity of Mach 1 are discussed. The application of the supercritical wing to this flight regime are discussed. Research work and flight tests performed by various American companies are detailed.

Seventeen years ago an unknown American aerodynamicist made headlines in the world press. The young doctor, Richard Whitcomb, obtained the much-sought-after Collier trophy, which is awarded for outstanding contributions in the area of aerodynamics. At the time, the research results which Dr. Whitcomb had obtained represented a sensation for the research community. The "area rule" which he discovered was looked upon as the most important single breakthrough in the history of aviation since the jet engine was developed. Very soon after this these results were applied to practice: for example, there were the "wasp body fuselages" of high velocity attack aircraft such as the Convair B-58 Hustler, Convair F-102 Delta Dagger and Northrop F-5, which reduces the wave drag of these aircraft considerably when they fly through the velocity range around Mach 1. At present Dr. Whitcomb is one of the leading aerodynamicists in the world, and one of his idols was the American inventor, Thomas Alva Edison. The winner of the Collier Trophy in 1954 is today a scientist at the Langley Research Center of NASA at Hampton, Virginia. At the present time he is attempting to find commercial applications for another new invention in which he was also a participant. At the present time, specialists look upon the explanation of the flow conditions around the so-called "supercritical wing" /40*

*Numbers in the margin indicate the pagination in the original foreign text.



The supercritical wing is the most noticeable feature of this futuristic jet aircraft which technicians and scientists of the Convair Aerospace Division of General Dynamics envision for 1975-1985. Other features: 20% weight-saving compared with present-day jets and cruise velocities around 1000 km/h. (Photograph General Dynamics) as the most important advance in aerodynamics since the area rule, because the first flight test results of this wing concept are now available. /42

Mach 0.8 — The Critical Limit

It is not generally known that present-day aircraft fly in a velocity range which corresponds to only 80% of their performance potential. At an altitude of 35,000 feet, the cruise velocity of conventional jets is approximately 0.8. This fact may be surprising at a time when the concepts of power and cost effectiveness are extremely important in aerospace technology. Advanced technology is continually displacing less advanced technology. The flight performance is not completely taken advantage of due to an aerodynamic phenomenon which occurs when conventional wings reach a flight velocity in the vicinity of Mach 1. Anyone who is familiar with the bases of aerodynamics knows how the lift force is produced on a wing having a "normal profile". The air flowing over the top side of the wing has a higher flow velocity than along the lower side of the wing. According to the flow law, there is a lower static pressure in the flow having the higher velocity, that is an underpressure (suction). On the other hand, there is an increase in the static pressure in the air flowing below the wing at a reduced velocity. All forces together produce the lift force. Now if the wing enters the Mach 1 limiting region, then the air flowing over the wing reaches sonic velocity earlier than does the flow over the under side of the wing or at other points of the profile. This brings about local shock waves at several points along the upper side of the wing. These produce strong pressure fluctuations and a sudden drag increase as well as strong oscillations. The drag increases so much in the vicinity of velocities near Mach 1 that it is not economical to use these velocities in aviation. Thus, for example, about 50% more engine performance is required in this limiting range to produce a velocity increase of about 10%. Also, the passengers could not endure flights in this velocity range. It is no longer possible to have a quiet and undisturbed flight. Instead, the fuselage carries out strong flutter oscillations.

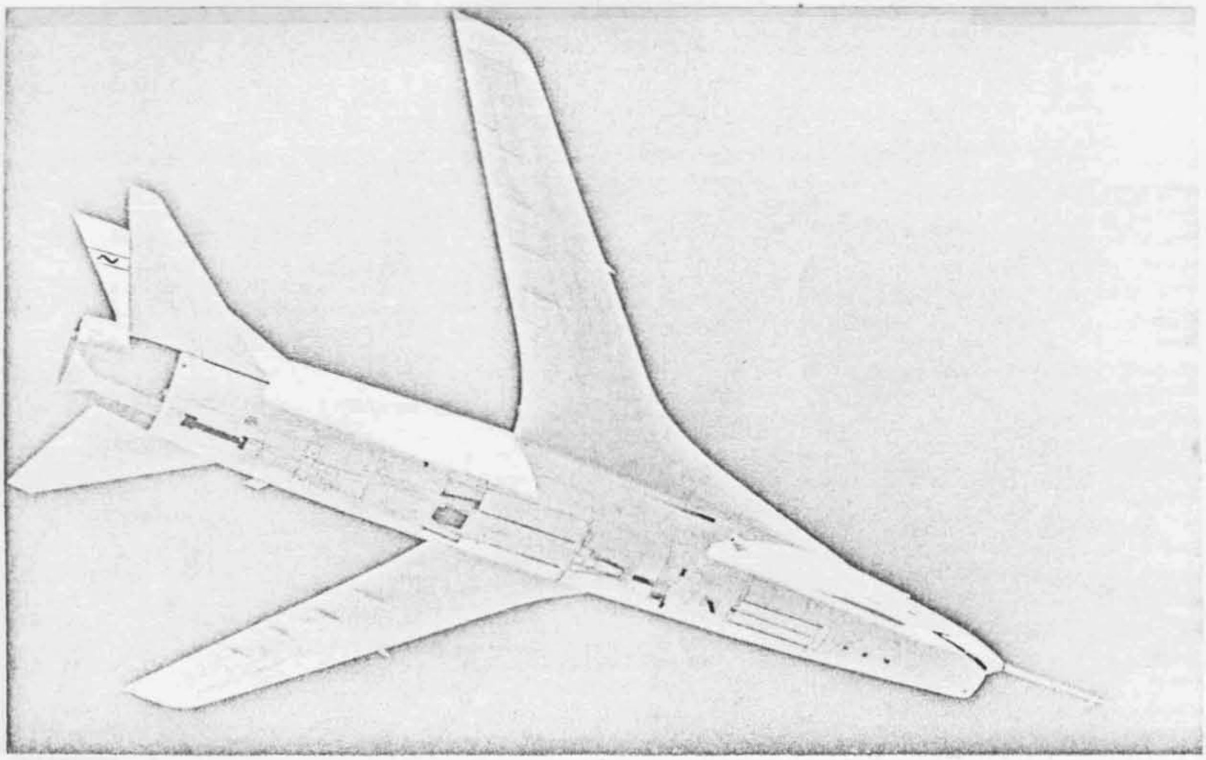
These problems have been known since the beginning of jet-propelled aviation, but they have been accepted. Certainly attempts have been made to make improvements, such as increased wing sweep-back or reduced wing thicknesses, which delay the drag increase and reduce the tendency to flutter. At the same time, these measures introduce increased structural weight and problems at the lowest velocity ranges. In addition, the takeoff and landing distances were increased.

The Supercritical Wing — a Solution

A very promising formula without compromises for the solution of these problems began to appear. After five years of intense research work, and after carrying out thousands of test series, Dr. Whitcomb reached the threshold of practical testing of his idea, the supercritical wing. In order to remove the phenomena which occur around Mach 1 on a normal profile wing, Dr. Whitcomb essentially changed the wing profile. The curved arcs of the upper side of a normal profile have relatively large curvature. The curvature is not as great along the under side of the profile. One of the main features of the supercritical wing profile is the small curvature along the top side of the profile, and the very pronounced concave curvature along the lower side of the profile trailing edge. It is immediately apparent what happens. As Mach 1 is approached, the tendency of the flow to separate from the top side of the wing surface is smaller in the case of the supercritical wing profile than for the normal wing, because the profile curvature is considerably less. However, there is a loss in lift (smaller flow velocity produces a smaller suction effect). However, this is balanced by the peculiar concave curvature at the profile trailing edge.

From the Laboratory to the Test Flight

After model wind tunnel experiments over several years at the Langley Research Center and after endless testing and refinements of the initial configuration, the final design finally crystallized. Laboratory experiments were no longer sufficient. It was time to "leave the nest" and to try the idea in a test flight. For this purpose, NASA awarded a 1.8 million dollar contract extending over nine months to the Los Angeles division of North American Rockwell for the construction and production of a supercritical wing according to Whitcomb's data. The wing was to be mounted on a modified version of a LTV F-8 Crusader, which was supplied by the United States Navy to NASA. The contract was monitored by the Flight Research Center of NASA at Edwards in the Mojave desert of California, where the test flights of the unconventional wing were to be carried out. The manufacturing problems were much more difficult than in normal aircraft construction, because an exact correlation between the flight test data and the wind tunnel values had to be achieved in the supercritical wing program. The wing deflection during cruise flights had to exactly correspond to the position of the model wing in the wind tunnel. This meant very strict adherence to specifications and very small tolerances for the wing deflection, which could only be guaranteed by an experienced and large airframe firm. After delivery of the wings to NASA, the wing was mounted on the modified F-8 Crusader at the NASA facilities. Load tests, test instrument installation work and calibration tests were carried out over several months. The NASA test pilot, Thomas McMurtry, took off on March 9, 1971 on the first flight. The first test phase was carried out by McMurtry together with his colleague Gary F. Krier and was aimed at collecting the first flight experience with the supercritical wing and at determining the effect of various flight velocities and flight altitudes on the wing behavior. It is now clear that the test wing does indeed confirm the predictions of the wind tunnel tests. During the last flight of the test phase I, the aircraft reached a maximum velocity of 1167 km/h at an altitude of 35,000 ft (10,675 m) on May 26, 1971. This velocity is slightly above the sonic velocity at this altitude. The maximum altitude at which the test aircraft carried out maneuvers was 46,000 ft (14,030 m). Just after this, a two-month interruption was used to remove slight aerodynamic irregularities along the upper side of the wing, such as protruding bolt heads. A network comprising 250 pressure sensors was installed which has the purpose of determining the position of and measuring the shock waves which occur in the air flow. This is extremely important for evaluating the supercritical wing concept.



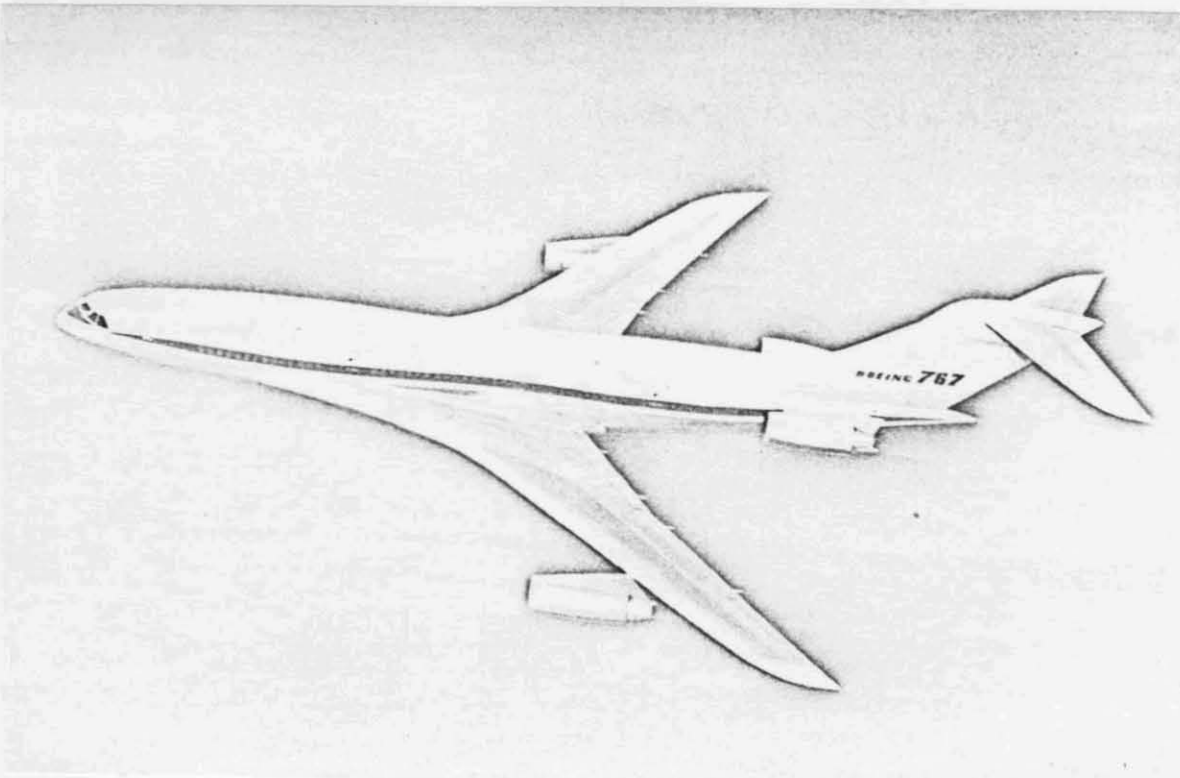
The aerodynamic shape of the supercritical wing is easily seen in this photograph of a modified LTV F-8 Crusader used in research. It is considerably different from wing shapes used today.
(Photograph NASA)

because its effectiveness depends critically on whether the shock wave is displaced in the direction of the profile trailing edge, in order to obtain a drag reduction of the desired amount. A second division of the North American Rockwell Corporation, the Columbus division, which worked on the supercritical wing research program, is working with a supercritical wing having a thickness ratio of 17%. It has the same critical Mach number as a standard wing with a thickness ratio of 12%. Therefore, the supercritical wing means an increase in absolute profile thickness of about 42%. This profile is being tested on a North American Rockwell T-2 C Buckeye Navy trainer under the sponsorship of NASA and will provide a direct comparison of a standard profile and a supercritical profile without making any other changes to the aircraft air frame or to the wing outline. This is different from the wing of the F-8 Crusader mentioned above, where the entire wing design was substantially modified in comparison with the original wing. According to Dr. Whitcomb, the advantages of his concept — that is, the performance increase brought about by the supercritical wing — can either be translated into increased flight velocities or increased wing thickness. Examples of this are the Crusader and Buckeye-wings, respectively. A thicker wing makes it possible to carry along considerably more fuel without the use of external tanks, which amounts to greater range. In addition, if a thicker wing is built, the wing structure can be made lighter for the same stiffness as in the case of the normal wing. Whitcomb states,"This is the advantage of the supercritical wing concept. In general, a performance increase between 15 and 25% can be reached, which does not necessarily have to be taken in the form of a velocity increase. Many airlines will probably increase the payload capacity instead and, therefore, reduce the fares. On the other hand, it is also possible to drastically increase the range, such as in the case of the T-2 C.

The United States Air Force also became interested in the supercritical wing after evaluation by NASA and the United States Navy. The Air Force Systems Command awarded a contract valued at over $2,414,900 on June 16, 1971, to the Convair Fort Worth Division of the General Dynamics Corporation for the design and production of a supercritical wing. It is to be mounted on a modified General Dynamics F-111-Swing-Wing aircraft in conjunction with the NASA. Under this cost-plus-fixed-fee contract, the final value of which is $12,900,000, the fuselage modification work of the F-111 and the integration of the fuselage and the wings will be carried out. The main goal of the contract is the evaluation of the application possibilities of supercritical wing technology to highly maneuverable and advanced aircraft. This means the evaluation of the supercritical wing as applied to swing-wing aircraft. The flight test program will be carried out jointly by the flight research command of NASA and the Air Force Flight Center at Edwards Air Force Base. At the time this article was being written, the project was just becoming "frozen". The first flight will take place during the middle of 1973.

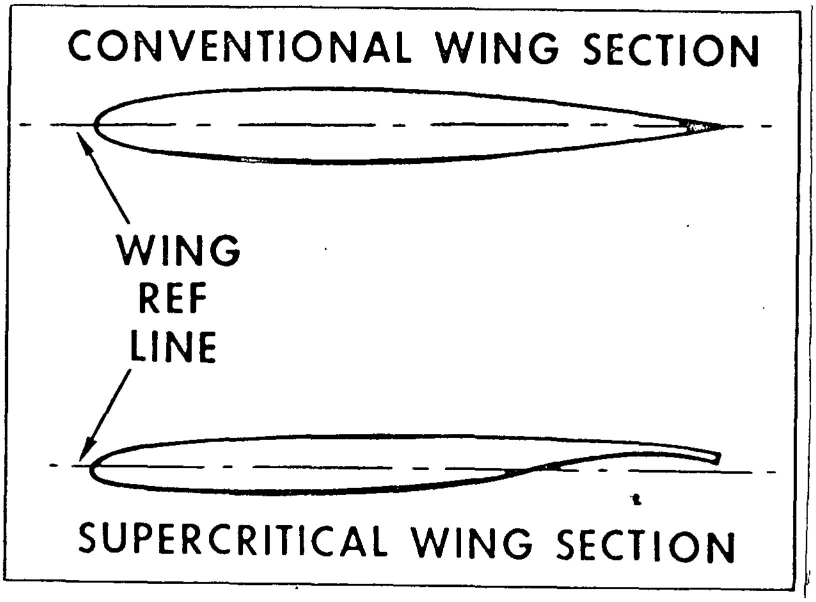
Application Studies

Before the supercritical wing technology can be applied in practice, such as in the form of advanced commercial aircraft, extensive research and development will be necessary. At the present time, almost every large firm in the United States aerospace industry is performing application studies. In April 1971, the NASA-Langley Research Center awarded three contracts valued at $1,000,000 each to three firms, the Boeing Company, Lockheed-Georgia Company, and Convair Aerospace Division of General Dynamics. Under these contracts, future studies of commercial aircraft for the years between 1975 to 1985 will be carried out. They will be based on advanced technologies such as the supercritical wing and the area rule. Not much of the work performed by Lockheed has yet been published. First project studies performed by Boeing and Convair are now available. Thus, Lloyd T. Goodmanson, the Boeing director for advanced transport aircraft program, presented background material for the three studies now underway at Boeing. This was presented at the 12th Anglo-American Aviation Conference in Calgary, Canada, and sponsored by the Royal Aeronautical Society, the Canadian Aeronautics and Space Institute and the American Institute of Aeronautics and Astronautics. He stated that, "A commercial aircraft traveling close to the speed of sound will be operational before the end of this decade". Under this NASA contract, Boeing scientists have investigated aircraft configurations for various flight velocities and aerodynamic designs, considering factors such as noise development, environmental acceptability and range economics. A comparison was made between a sample aircraft operating just below acoustic velocity (Mach 0.98), a transonic aircraft (Mach 1.2) and an aircraft flying at Mach 0.84, which corresponds to present-day commercial aircraft and has /46
conventional fuselage and wing shape, but is based on advanced manufacturing technology. According to Goodmanson, the operational costs of the sample aircraft flying close to the speed of sound are 5% lower than for the Mach 0.84



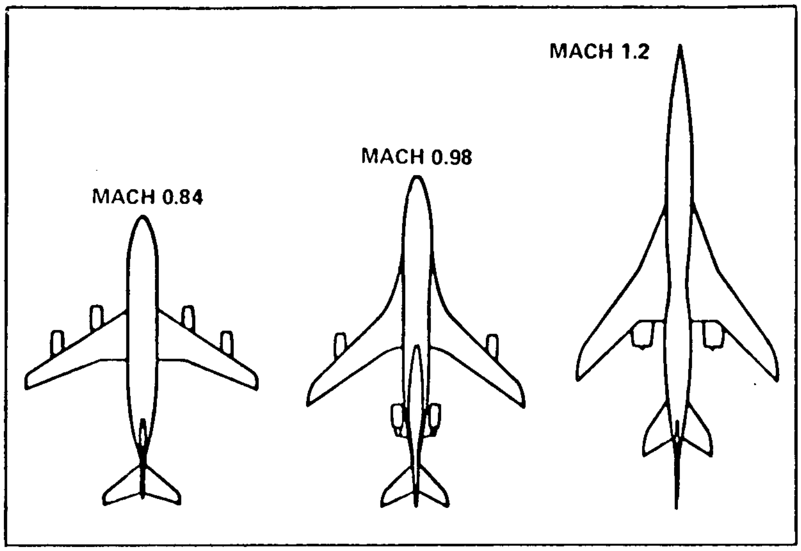
The Boeing 767 is one of the many advanced transport programs investigated in application studies for the supercritical wing being performed by the Boeing division. (Drawing: Boeing)

aircraft. The cruise velocity exceeds that of the Mach 0.8 aircraft by 150 km/h. The operational costs can be reduced by about 15% as compared with the costs of the Boeing 707/McDonnell-Douglas DC-8 class. Goodmanson also stated that the studies show that the Mach 0.98 transport aircraft equipped with 200 seats has operational costs per mile which are 15% lower than the three-jet wide-body aircraft which are now appearing on the market. Boeing at the present time favors the Mach 0.98 design, which has a supercritical wing, four engines (two of which are far out on the wings and two in the fuselage aft section), and a fuselage which is designed according to the area rule. The passenger

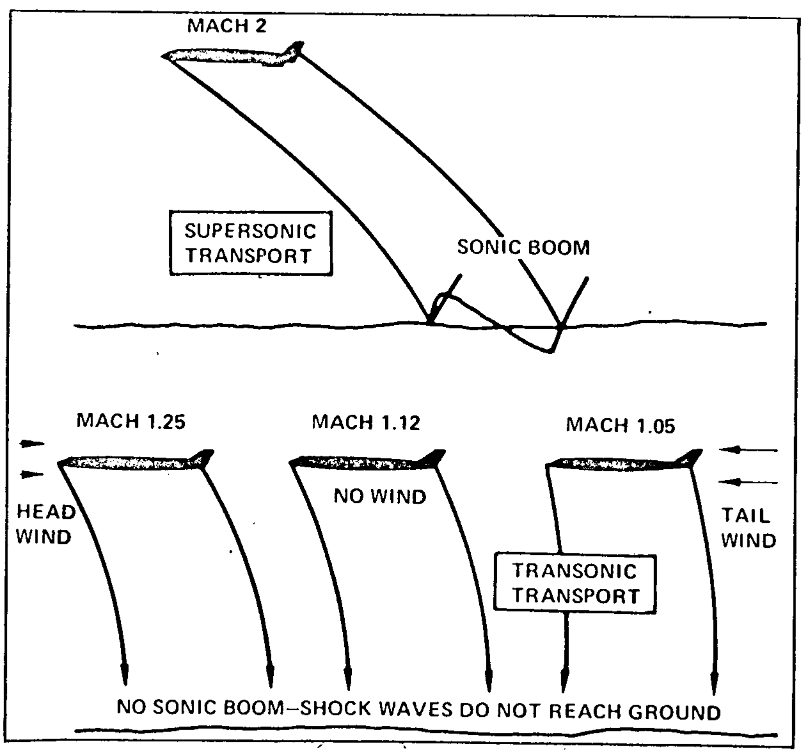


Comparison between the normal (top) and the supercritical wing profile (bottom): slightly curved profile topside, characteristic concave curvature along the bottomside of the profile trailing edge. (Drawing: NASA)

cabin has two aisles and at least six seats next to each other. According to Goodmanson, an airliner designed in this way would not only be more favorable regarding economy and flight velocity than aircraft of the 707/DC-8 class, but the noise level would be lower, and the passenger comfort would be greater. Six hundred hours of wind tunnel tests carried out at Boeing have led to the conclusion that the 0.98 Mach aircraft should be developed, which would be used at an altitude of approximately 14,000 m. Even though the Mach 1.2 aircraft flies faster than the speed of sound, there will be no supersonic boom on the ground because certain wind conditions and temperature conditions can be taken advantage of. In spite of the fact that progress has been made in these areas, Goodmanson does not believe that their time has yet come. In order to guarantee economical operation, considerable refinements to the design would have to be made, in order to achieve drag reductions and engine noise damping.



Top: Aerodynamic comparison of aircraft with the same payload capacity but varying velocity performance. Left, conventional Mach 0.84 jet; center and right, Mach 0.98 and Mach 1.2 studies, respectively.



Below: According to investigations performed by Boeing the shock waves do not reach the ground for transonic velocities (below). (Drawing: Boeing)

According to the Convair Division of General Dynamics, the aircraft of the future will weigh approximately 20% less than present-day aircraft and it will be possible to build it and operate it more cheaply. This is because of the increased use of plastic components. Just like Goodmanson, Ken Carline, director of the General Dynamics Programs for Advanced Transport Technology at the Fort Worth facility, believes that high subsonic velocities can be reached, 1060 km/h at an altitude of 12,200 meters, by using supercritical wing profiles and fuselage shapes designed according to the area rule. He also believes that, for the same amount of fuel as for conventional jets, it will be possible to transport larger payloads over larger distances, and that the flight characteristics in the transonic velocity range can be considerably improved. It is possible that the air frame, wing surfaces and possibly also fuselage components or the entire fuselage of a transport aircraft designed by General Dynamics will be made of graphite fiber reinforced plastic, which is lighter than the light metal alloys used today. As Carline states, "Large aircraft components can be made in presses by using bonding materials". A weight reduction of 20% and considerable cost savings are possible by avoiding the conventional cell covering technologies. The surface quality of transport aircraft of the future which General Dynamics is studying will also be considerably better than in the case of present day jets, because there will be no rivets and less joints. Carline states that wings made up of composite materials and advanced flight control installations should make aircraft travel during the 80's much more comfortable for the passenger than is the case today. Transducers in the flight control installation will detect turbulence phenomena and will provide for instantaneous equalization by appropriate commands which would result in deflections of the wing. General Dynamics is working closely with the engine manufacturers in order to develop new noise suppression technologies for the aircraft to be used between the years 1975 and 1985. Carline believes that the noise level of aircraft engines can be lowered on the order of 50%. Carline and NASA believe that long-range transport aircraft of the future will exceed present-day aircraft in terms of flight performance, economy, safety, and comfort. At the same time, they will produce less noise and poisonous substances than conventional jets.

The engineers and researchers responsible for modern technology at the Lockheed-Georgia plant have been carrying out studies over several years based on the research results on the supercritical wing of Dr. Whitcomb. In addition, Lockheed is also investigating transport aircraft with high velocity performance as well as the application of unconventional materials in aircraft construction. They are attempting to reduce overall weight. A four-jet, Mach 0.98 intercontinental transport aircraft for 400 passengers is being investigated within the framework of the NASA contract mentioned above, which will run for thirteen months. The future technology developed by Lockheed will be investigated further within the contract. They also wish to determine how much modern technology in the fields of aircraft procurement and operation can be paid for by the airlines. Lockheed-Georgia is considering the time when the airlines will be buying new, high-performance aircraft so that they may meet the growth rate in passenger aviation which is now predicted for the 80's.

The following question arises if one considers Dr. Whitcomb's research work and the now almost fever-like activity of NASA and the United States aerospace firms in the area of the supercritical wing. Why was this revolutionary concept not studied earlier? Dr. Whitcomb once retorted: "Why doesn't one think of an invention earlier?" The reason why supercritical wing research started relatively late is because the research and development in the United States was concentrated on the supersonic flight regime and its fascinating possibilities, without considering the possible improvement possibilities of the aerodynamic design of subsonic jets. Dr. Whitcomb believes that, even in the era of supersonic flight, more than 80% of the passengers will travel on subsonic airliners. This is certainly reason enough to improve the economy of the jet transport aircraft which operate in this velocity range. Certainly, the concept of the supercritical wing represents a jump ahead.

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